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## PREDICTIVE & PROGNOSTIC CONTROLLER FOR WIDE BAND GAP (SILICON CARBIDE) POWER CONVERSION (PREPRINT)

**Gregg Davis, Leo Casey, Brett Jordan, Jim Scofield, Kirby Keller, Jim Sheahan, Jeffrey Roach, Michael Scherrer, and Ranbir Singh**

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**14. ABSTRACT**
This report was developed under a SBIR contract. This paper presents an approach to predictive control and prognostication intended to increase the confidence levels for power converters in aerospace applications. One goal of this work is to accelerate the adoption of new technologies, such as advanced power semiconductor devices. While the devices are immature the technology provides significant overall performance advantages. Using prognostication it is hoped to significantly increase the confidence levels for successful mission completion and so overcome reservations about adopting these new technologies. The methodology uses predictive modeling and simple, robust, sensing, attempting to avoid excessive sensing requirements in the prognostics of complex converters. This approach requires detailed knowledge of the dominant aging and failure mechanisms, the physical driving forces behind these mechanisms and the observable precursors of failure. The precise history of the power converter system, combined with measurement and modeling, can then predict whether the system can operate successfully for a given time duration, with a high degree of confidence.

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# Predictive & Prognostic Controller for Wide Band Gap (Silicon Carbide) Power Conversion

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*Abstract*—This paper presents an approach to predictive and prognostic control, combining prognostics with predictive control to extend life., which is intended to increase the confidence levels for power converters in aerospace applications. One goal of this work is to accelerate the adoption of new technologies, such as advanced power semiconductor devices. While the devices are immature the technology provides significant overall performance advantages. Using prognostication it is hoped to significantly increase the confidence levels for successful mission completion and so overcome reservations about adopting these new technologies. The methodology uses predictive modeling and simple, robust, sensing, attempting to avoid excessive sensing requirements in the prognostics of complex converters. This approach requires detailed knowledge of the dominant aging and failure mechanisms, the physical driving forces behind these mechanisms and the observable precursors of failure. The precise history of the power converter system, combined with measurement and modeling, can then predict whether the system can operate successfully for a given duration, with a high degree of confidence. The information could also be used to guide decisions about the future use or loading of specific converters in larger, parallel, redundant systems.

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## 1. INTRODUCTION

As technology migrates towards more-electric and all-electric systems, it is only fair to acknowledge that many degradation mechanisms in mechanical systems are relatively slow acting, while electronic failures appear to be abrupt and unpredictable. Leaking hydraulic systems retain some level of functionality, but electrical drives tend to either work or not. This typically leads to redundant, and fail safe, designs, and shortened maintenance cycles to avoid approaching the effective "life" of the component. The work described in this paper is part of an effort to use Prognostic Control to develop a "gas gauge" of health or robustness for Power Conversion Electronics. This should give a more gradual and deterministic appearance to the aging and failure of power electronic systems. This will allow each unit to be treated based on its individual operating history as opposed to the maintenance cycle for the vehicle/aircraft itself.

The Prognostic Control we describe here is closely related to in-situ, or in-vehicle, health monitoring technology (IVHM), which recognizes changes in system behavior, both coarse and subtle, which is then used to predict future, or sometimes imminent, failure of critical systems. An example of this type of health monitoring includes bearing monitoring systems that sense bearing vibrations and temperature [1]. More advanced systems monitor high frequency vibrations [2], that essentially detect ablations of individual balls in the bearing race that foreshadow failure mechanisms by some tens of thousands of hours.

Where the precursors of failure can be detected and where the actual failure dynamics develop this slowly, this IVHM approach is a powerful tool for both predictive maintenance and calamitous failure prevention. The Prognostic Control approach, by contrast, utilizes models of the system, including a model of failure mechanisms and the drivers/accelerators for these mechanisms, that is then combined with the operating history of the unit to predict the useful service life remaining for the device or system. This is, by definition, a statistical approach to failure prediction, but, well-manufactured power converters have been shown to fail in a relatively deterministic way, with a reasonably tight spread between similar units [3], [4].

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The initial focus of this work is to use the knowledge of the operating and environmental history of a power converter to predict future health and the likelihood for subsequent successful operation of the converter. The level of the "gas gauge" is determined by weighing the history of stress seen by the device, the inherent weaknesses and aging mechanisms that these stressor act on to promote the ultimate demise of the unit and the interaction of these stressors, where appropriate. Knowing with a high degree of confidence that something will last for a given period of time can be extremely valuable in mission critical applications. The second focus of this effort is to characterize and model aging mechanisms associated with Silicon Carbide (SiC), or other wide band gap (WBG) semiconductors and their application. This can involve mechanisms in the semiconductors themselves, the associated high temperature (hi-T) packaging that is required for them to achieve their full potential, or other elements that are different from the traditional practice of Power Conditioning. The intent is to use the Prognostic Control techniques to significantly increase the confidence level of successfully using these new, advanced, semiconductor technologies in real world applications. This could well be the deciding factor between electric/electronic systems and more traditional electro-mechanical solutions in environments where weight, volume and reliability are of paramount importance, such as in aircraft and space applications.

*Comparison with Human Health Prognostics*

Modern medicine is an interesting mix of prevention, diagnosis, and treatment, with the admonition that it is still more art than science still rather common. Biochemists would have us believe that it is ultimately both causal and predictable, while extremely complicated and only partially understood. Meanwhile, today in addition to recognizing and responding to direct physical symptoms, medical clinicians rely strongly on family history, individual history, environmental conditions or exposures and lifestyle to ascertain the likelihood of specific diseases. While there are direct and often devastating genetic diseases, many human diseases are believed to have both a genetic and an environmental component. Many cancers fall into this category. Similarly, power converters have finite lives because the materials age, both naturally and due to stressors such as Temperature, Temperature Shock, Thermal Cycles, Vibration, Humidity, and the like.

Just as the genetic signature of a human being is believed to be the blueprint of potential strengths and vulnerabilities, so the materials and manufacturing process of power converter set the boundaries on the converter's life. The family medical history of a human, not to mention other familial historic behaviors, basically averages the genetic susceptibility across other members of the same class. In the power converter case this becomes the history of the model and possibly related models of the particular converter design. The lifestyle, the stress and the exposure that is considered in human disease are equivalent to the operational and environmental forces on the power converter that we have discussed.

## 2. ADVANCED POWER CONVERSION

In general modern power conversion uses high speed switching to synthesize waveforms for inverters, or average values in the case of converters, in conjunction with reactive components that are used as filter elements to smooth the switched waveform. Occasionally the reactive elements are used to both store and transfer energy as well. Meanwhile, the electronics is controlled by signal level electronics and heat transfer and heat removal are key elements to keep the internal temperature rise within bounds. Ultimately these components form a system whose key metrics are size, weight, efficiency, bandwidth (speed), ruggedness including overload capability and lifetime. These metrics are invariably traded off against each other, particularly size and weight vs efficiency vs reliability. Converters could easily be made smaller, particularly by using higher switching frequencies, but at the cost of efficiency, temperature and, ultimately, reliability.

Switching power conversion has developed from the power bipolar technology of the 1960s and 70s, the MOSFET technology of the late 1970s and the IGBT technology of the late 1980s. Subsequently, incremental advances in thermal, reactive, switching and control technologies have allowed Power Converters to evolve to today's state-of-the-art. The one element of Modern Power Conversion that would allow a dramatic, transformative development would be a major advance in the power switching device. This, and the fact that some application environments are simply incompatible with the Voltage and Temperature capability of Silicon has motivated extensive work on the Wide band Gap Semiconductors and Silicon Carbide in particular.

## 3. POTENTIAL OF SILICON CARBIDE

SiC enjoys three key materials advantages over Silicon for power semiconductor applications.[5] These advantages are highlighted in Table 1, which compares Silicon to several Wide Band Gap materials. The three main advantages are higher breakdown field (10x), higher thermal conductivity (3x) and wider bandgap (3x). Higher breakdown field allows power devices with shorter drift regions, leading directly to lower resistance. Higher thermal conductivity, in turn, means that any heat generated within the power device can be more easily removed.

**Table 1: Some Critical Properties of WBG Semiconductors**

| Property | Si | 6H-SiC | 4H-SiC | GaN | Diamond |
|---|---|---|---|---|---|
| Bandgap $E_g$ (eV) | 1.1 | 3.0 | 3.3 | 3.45 | 5.45 |
| Dielectric Constant, $e_r$ | 11.9 | 9.7 | 10.1 | 9 | 5.5 |
| Breakdown Field, $E_c$ (kV/cm) | 300 | 2500 | 2200 | 2000 | 10000 |
| Electron mobility, $m_n$ ($cm^2$/V-s) | 1500 | 500 | 1000 | 1250 | 2200-4500 |
| Hole mobility, $m_p$ ($cm^2$/V-s) | 600 | 101 | 115 | 250 | 1600-3000 |
| Thermal Conductivity 1 (W/cm-K) | 1.5 | 4.9 | 4.9 | 1.3 | 22 |
| Thermal expansion ($10^{-6}$)/ºK | 2.6 | 3.8 | 4.2 | 5.6 | 1-2 |
| Saturated $e^-$ Drift Velocity, $n_{sat}$ ($10^7$ cm/s) | 1 | 2 | 2 | 2.2 | 2.7 |

The wider bandgap of the material translates into semiconductor devices with higher activation energies, and therefore superior temperature and radiation performance. The dramatic improvement in theoretical device performance is largely derived from the higher electric field strength, which permits proportionally smaller drift regions.

Presently, medium voltage SiC devices (600V –1200V) achieve greater than 100 V/μm of drift region compared to the 10 V/μm of Si. At the same time the higher gradient of the electric field in the drift region of the SiC power device means that it can be much higher doped than in Si. The overall device advantage is an approximately two orders of magnitude reduction in the resistance of the drift region of the Power device. The theoretical limits of SiC are compared to those of Si in Figure 1 [6].

The next significant point is the superior heat conductivity of the material. Whatever heat is produced is easier to get out, AND as importantly for sharing and paralleling in dynamic conditions, the heat spreads across the device more quickly. For power devices where the heat is typically produced several 100 microns below the surface this is quite significant. Also, most device failure mechanisms tend to be localized phenomenon where, for instance, a small avalanche area causes a filament of avalanche current with local overheating and ultimately device failure. The ability to spread the heat rapidly can prevent this failure.

The wider bandgap could be regarded as a two edged sword as junction drops are proportionally higher, but the inherently high temperature and radiation tolerance make Silicon Carbide and other WBG materials usable in extremely harsh environments that have long been considered inhospitable to conventional electronics

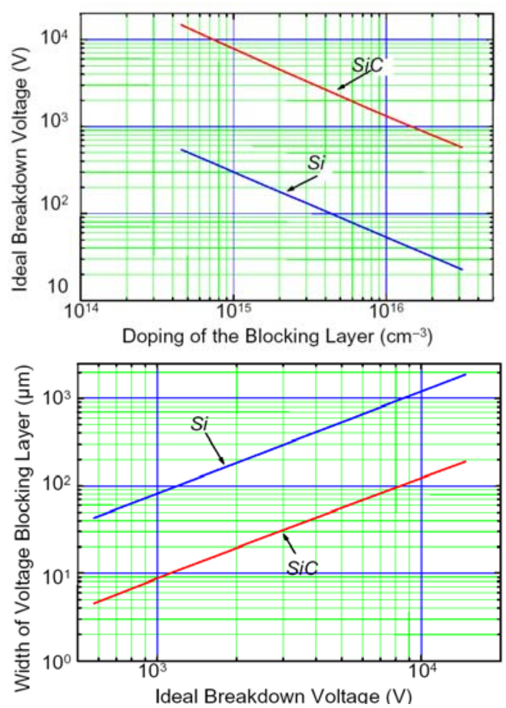


Figure 1: Theoretical Limits of Si and SiC

A final advantage of SiC, if indeed that is the appropriate term, as a power semiconductor material is the dramatically lower minority carrier lifetime which permits minority carrier devices, such as bipolar junction transistors, with very fast switching times. The short lifetimes are largely due to the imperfections in the crystal structure, as opposed to any inherent feature of the technology. To the extent that base and drift regions can be made much smaller than in comparable Si devices then the amount of stored charge can also be much smaller and so faster devices can be made without making too big a compromise in the gain, or beta, of the device. In general speed and gain can be traded off in bipolar devices and this holds true for SiC but again the gain-bandwidth product is much higher than in Si.

SiC is a unique material, with many crystal structures and no liquid state. Some issues that arise affect the resulting semiconductor devices such as the incomplete ionization of dopants at room temperature, leading to strong temperature effects, problems in achieving stable highly doped p-type material and the like. Nevertheless, in the last 5 years the advances in processing and materials have been truly dramatic. Fueled by the demand for high-quality 4 inch SiC wafers as substrates for Gallium Nitride LEDs, the industry in the primary manifestation of Cree, has developed high-quality wafers and now has more than three suppliers of commercial SiC Schottky diode die (Cree, SiCed, Rockwell). The improved wafer quality has permitted production of Schottky die approaching 5.6 mm by 5.6 mm with developmental active SiC devices of 3 mm by 3 mm and experimental devices, such as GTOs, as large as 1 cm by 1cm.

At the same time active devices such as JFETs, HEMTs, MOSFETs, Bipolars, GTOs, BiFETs have been demonstrated and developed such that they not only demonstrate functionality but also actually achieve performance levels that approach theoretical limits. These devices in turn have been applied in real systems, such as motor drives [7] and power converters. Admittedly, there are still many device related issues, particularly associated with oxides, threshold levels, ohmic contacts, ionization levels and dopant levels not to mention some of the underlying crystal defect issues, which we will develop further below in considering physical modeling of these devices. The capability to provide prognostic control for SiC power converters/inverters should accelerate the adoption and ultimate application of this technology.

The ideal in power device fabrication is to produce large quantities of essentially identical, high quality, devices with minimal aging mechanisms and high level of robustness. Some level of consistency can be tested and sorted into a process, but a relatively good measure of process maturity comes from actual device-to-device consistency. A summary of our knowledge of the state of the art in SiC devices is shown below in Table 2. This table is based on SatCon's characterization of devices, and from data provided by Cree, Northrop and SemiSouth, or occasionally gleaned from other sources. These are "real" devices that have come from process runs with reasonable yields as opposed to "best of" or "hero" results. The definition of rated current we have used, as opposed to peak current, corresponds to a 1% conduction loss at half of the devices breakdown voltage. To illustrate this by example, a 600V switch could be applied in a 300V inverter with 1.5V drop per switch for a series drop in any conduction path for 3V total voltage drop.

**Table 2: State-of-the-Art SiC Devices**

| Device | Voltage (V) | Current (A) | Demonstrated Switching times |
|---|---|---|---|
| Schottky | 600<br>1200 | 150<br>75 | ns |
| PIN | 20,000 | 20 | ~10ns |
| Bipolar | 1200 | 20 | ~50ns |
| MOSFET | 1200<br>10,000 | 20<br>10 | ~20ns<br>~30ns |
| JFET | 10,000<br>1,200 | 1<br>20 | ~20ns |

*Impact of SiC on Motor Drives*

This discussion addresses motor drives rather than power converters in general as this has been the focus for development of the prognostic techniques. Based on our understanding of power Si Inverter technology used today, and the potential of SiC we can predict somewhat as to the likely impact SiC technology will have on power conversion for motor drive applications. This assessment is based on going beyond characterization of available devices to develop device and system models for SiC system designs and the ability to project system performance. Table 3 gives some estimates of improvements in power density, cooling requirements, system response times, overload capability and reliability.

The intermediate column shown in Table 3 is for hybrid Si/SiC technology, where SiC high-voltage Schottky rectifier devices are used in conjunction with Si IGBTs. This builds on the already commercially available devices. Not all components of a typical inverter are reduced by raising the switching frequency, and even the components that scale easily, such as magnetics, have limitations on operating frequency due to inherent materials limitations.

**Table 3: Projected System Advantages with SiC**

| | Silicon SOA | Hybrid Si/SiC Design | Full SiC Design |
|---|---|---|---|
| Size/Density/Efficiency | 10 -- 100 W/in³ | 15 -- 150 W/in³ (70% Vol., 50% Switching, ~75% P) | 35 -- 350 W/in³ (30% Vol., 20% P) |
| Cooling | 80ºC max. liquid or 25 ºC Air | 80ºC max. liquid or 25 ºC Air | >100ºC liquid or 40-50 ºC Air |
| Response Time | 10 ms for 5.6 kHz with V and I loops | 5 ms for 10 kHz with V and I loops1mS for 100kHz with dead-beat control | 50 µS for 100kHz with dead-beat control |
| High Temperature Design | Si limits entire system to < 125ºC | Si limits entire system to < 125ºC | Partial High-Temperature design then eventually complete High-Temperature design if needed (analog degradation) |
| Overload Capability | 100-500 ms | 2+ seconds | 10+ seconds |
| Robustness/Reliability | 10-20,000 hr. MTBF | 20-50,000 hr. MTBF | 50-100,000 hr. MTBF |

So while SiC will enable 10x increase in frequency the true benefit in terms of system volume is projected to be around 3x, with the benefits coming principally from reduced filtering requirements and/or smaller heat sinks. The "and/or" is an important point because if an advanced semiconductor technology, such as SiC, has much faster switching times than Si, then the choice is whether to save energy (increase efficiency) or instead to save volume and weight of the filter components, or whether ultimately to chose some mix of the two. In aerospace applications volume and weight are key design drivers, in some stationary applications efficiency is the dominant consideration.

As shown in Table 3 the effect of the filter elements being reduced by an order of magnitude is that the entire system volume and weight is expected to be 30% of the benchmark Si design. Alternatively the conduction and switching losses can be reduced by approximately 80% in the full SiC design. To complicate things even more, the 3x volume/weight tradeoff against the 5x efficiency (reduced dissipation) tradeoff is not independent of the 5x reliability improvement. As in many designs there is in fact a design triangle where the appropriate advantages need to be chosen based on some metric developed for that particular application.

## 4. APPLICATION EXAMPLE: MOTOR DRIVE

We chose as the demonstrator a 10kW motor drive developed for the Future Tactical Truck System (FTTS) being developed for the Army Research Labs (ARL). SatCon supplies variations on this design for several applications in the FTTS Hybrid Truck, from A/C compressor motor drive, to front and rear steering motor drives. This particular vehicle has front and rear steering

and due to the weight distribution the most onerous performance requirements are for the hydraulic pump motors for the rear steering system. The mechanical model drawing for the motor drive is shown in Figure 2.

Motor drives are more complex than dc/dc converters with the details of the losses and even the distribution of the losses between the different power semiconductor switching elements being a strong function of the load conditions. The load can be balanced, unbalanced, have complex torque/speed curves, have interesting if not bizarre dynamic behavior and the result is both complexity and uncertainty surrounding the actual device stresses. Only in completely symmetric inverters do the power switches share the current, power, and so losses, equally. Even then, the ratio of power dissipation between the active devices and the anti-parallel diodes is determined by the power factor, and the modulation index (in the case of a motor this is essentially determined by the back EMF) of the load.

This FTTS hydraulic motor drive system operates in a particularly aggressive thermal environment, nominally 65°C WEG as coolant, which makes it an excellent candidate for the prognostic control study and development. In reality the test trucks have exhibited or provided cooling fluids to the main cooling plenum of the motor drive with temperatures as high as 80°C. The Prognostic development program has complete access to the test stand, which includes dynamometer and thermal imaging as shown in Figure 3.

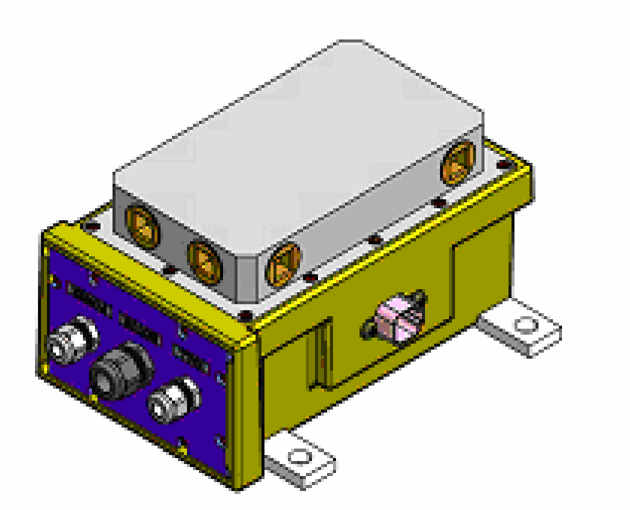

**Figure 2: 10kW Motor Drive for Prognostic Development**

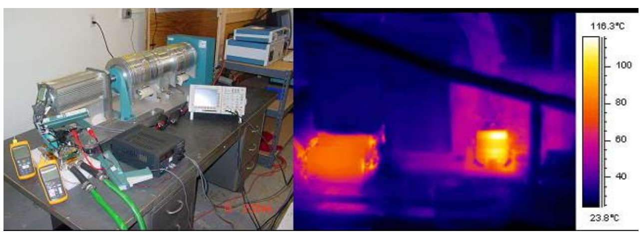


**Figure 3: Motor Drive Test Stand and Thermal Imaging**

When we studied the failure statistics for this particular motor drive we found that one particular power device repeatedly failed, namely the upper IGBT mounted in the middle of the unit. Study revealed that an asymmetry in the cooling system leading to a higher thermal impedance for some devices and the ability in the steering system application for the motor to experience hard stall for a period of seconds to tens of seconds before a hydraulic relief valve opened. This last, the stall condition, was an artifact of a software problem that drove the steering system hard up against mechanical stops and is not within the intended design space for the motor or drive. It is, however, a perfect example of the fact that subtle details in the load can have a strong determining effect on individual power device stresses in motor drive applications.

*Experimental Verification of First Order Thermal Impedance Models*

To facilitate the development of prognostic algorithms independent of the full motor and drive test stand a production brushless DC motor and its drive system were taken off the manufacturing line for bench testing. Figure 4 shows the motor and drive.

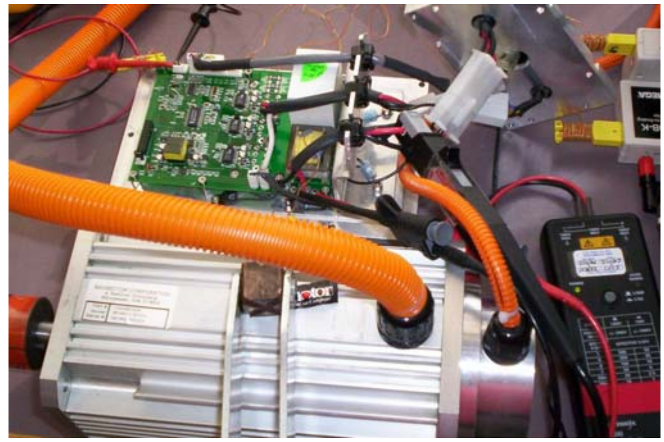

**Figure 4: SatCon BF46-H-500H BLDC Motor with Three-Phase Drive**

For this simple test stand the motor drive was loaded by connecting via shaft coupler to a similar motor acting as a generator. Data was taken from this test stand with the focus on measuring the voltage and current into the motor drive, as well as the case temperatures of the bridge transistors. Representative data is shown below for two load transients:

1. Stepping from unloaded (open circuit) to loaded

2. Stepping to a 33% increase in load

With the results shown in Figure 5 and Figure 6 below. These studies have verified that the overall thermal impedance can be modeled as a first-order network with the total system power transmitted as the driver (within the constraints of load dependent non-uniformities as discussed above).

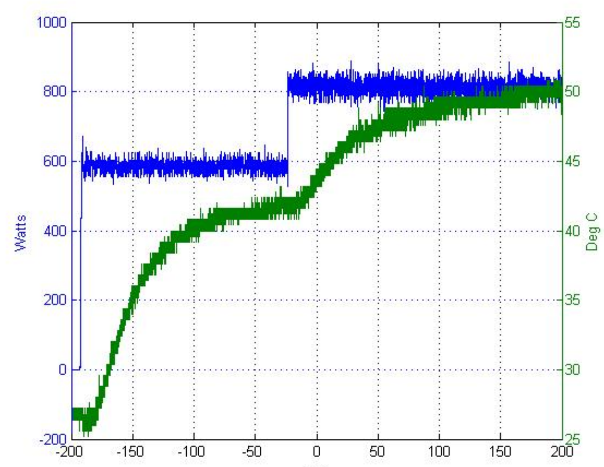


**Figure 5: Dynamic Response of Transistor Case Temperature to Step Change in Load**

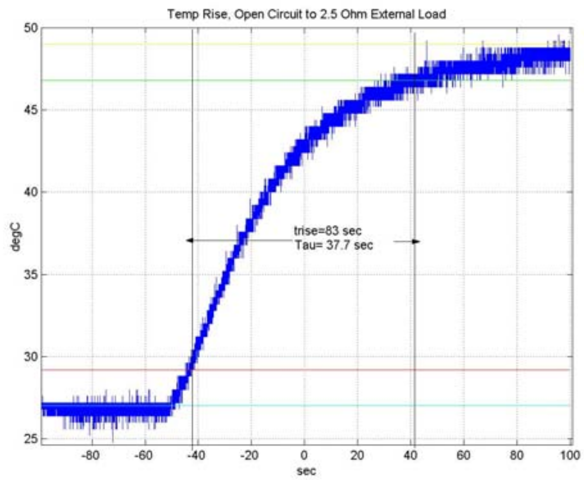


**Figure 6: Dynamic Response of Transistor Case Temperature to Step Change in Load**

*Temperature Profiling through Real Time Simulation with Appropriate Sensing*

At this point the sensed signals are V, I, $T_{CASE}$ and $T_{PLENUM}$. Knowing the switching behavior of the circuit, one can deduce the temperatures of all six bridge transistors without adding any additional sensors other than the two temperature sensors. The bus voltage is already sensed for the under-voltage lockout function, the device currents are already sensed for current-limiting, the baseplate temperature is already sensed for the thermal cutoff function, and the rotor position is fed into the motor controller. The Motor Drive has a dedicated microprocessor that today is used for CAN bus communications. We are presently modifying this circuit to implement the sensing of voltage, current, speed and switch position (particularly for stall conditions). The sensors we are adding to the basic circuit are an input current sensor and the two temperature sensors. Thermal imaging has shown that some of the input filter elements are running hot and so it is possible that we will add some sensing in this area as well. Further experimentation will define the sensing needed to support accurate prognostic control. Sensors negatively impact cost and reliability.

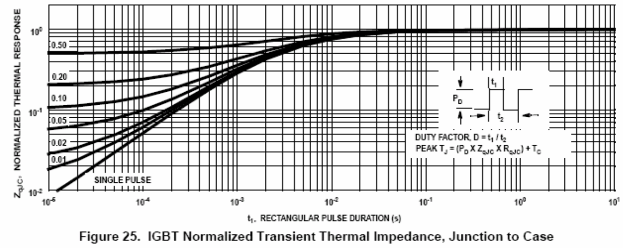


**Figure 7: Variation of Thermal Impedance with Pulse Parameters (FGH30N60 IGBT)**

*Electrical System and Device Simulations*

The criticality of full system simulations is very well illustrated in this program. For the Motor Drive failure modalities we have found it is critical to study the distribution of losses between the three phase bridge switches. We used PSIM (spell out first time) to develop a model of the motor drive and referenced the Motorola Brushless Servo Driver IC to develop an accurate model of the control as shown in Figure 8. Shown below in Figure 9 are representative load transient results from full system simulations.

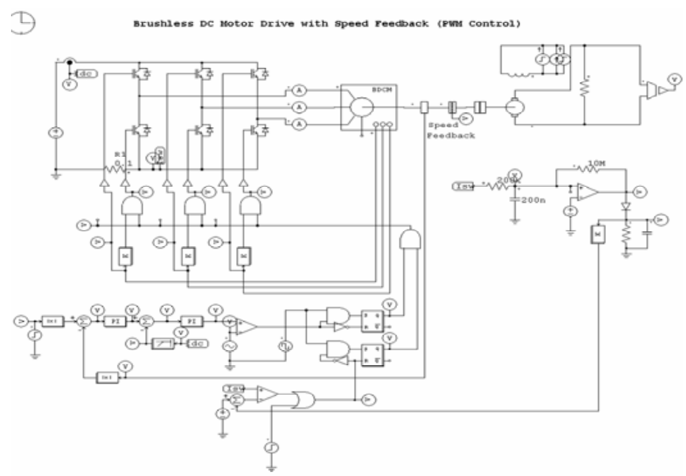


**Figure 8: Simulation Diagram of BLDC Motor Drive**

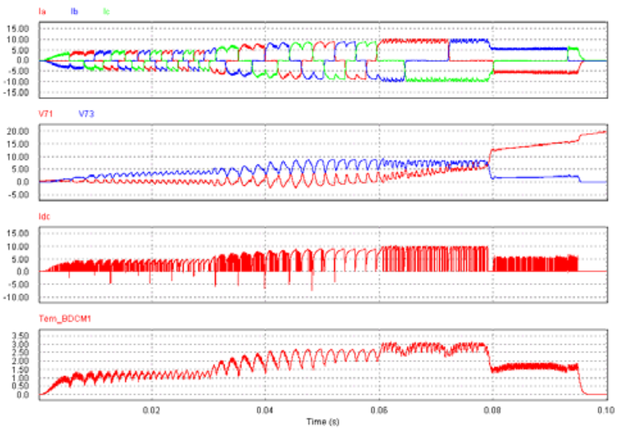


**Figure 9: BLDC Motor Simulation Waveforms**

## 5. Unique Failure Signatures in SiC Devices

One way of classifying ageing mechanisms in SiC devices is based on whether they are majority carrier devices or minority carrier devices because some materials defects and device fabrication methods have a stronger effect on minority carrier transport, while others do not. First, an extensive understanding of SiC-specific material defects were analyzed, then comprehensive physical models that determine device performance parameters were identified, and finally device characteristics that provide signatures for failures were identified. There are many material defects commonly observed in present-day SiC as shown in Table 4. Growth pits and carrot defects result from wafer defects that create adverse conditions for the realization of a perfect crystal structure during epitaxial growth. Temperature non-uniformities during epitaxial growth cause the appearance of triangle inclusions of different polytypes. Poor management of impurities or premature nucleations of SiC particulates cause the formation of comet tails and other defects.

**Table 4: Typical materials defects and their impact on devices.**

| Defect Type | Typical Densities | Affect on Devices |
| --- | --- | --- |
| Micropipes | 1-15 $cm^{-2}$ | <50% $E_{cr}$ |
| Carrots | 0.1-10 $cm^{-2}$ | $E_{cr}$, $J_L$, n |
| Major Pits | 1-100 $cm^{-2}$ | $E_{cr}$, $J_L$ |
| Screw Dislocation | $10^3$ $cm^{-2}$ | <80% $E_{cr}$ |
| Edge dislocation | $10^4 - 10^5$ $cm^{-2}$ | ?? |
| Low angle grain bound. | $10^2 - 10^3$ $cm^{-2}$ | $\tau$ - reduction, forward chars |
| Stacking Faults | 1-100 $cm^{-2}$ | $\tau$ - reduction |

*Reverse I-V characteristics of SiC devices*

When devices are in the reverse blocking mode, i.e. reverse biased Schottky and PN junctions, devices are expected to have low leakage current and have near-theoretical blocking voltage. From a reliability perspective, it is important to understand the affect of materials and processing defects on leakage current, total blocking voltage achieved, and sustainable avalanche energy achievable during breakdown.

Schottky devices are very sensitive to surface and morphological defects [8]. Even small areas with material defects that cause reduced metal-semiconductor barrier height, can dominate reverse blocking characteristics. This is because leakage currents in Schottky contacts are exponentially dependent on barrier height. Epitaxial growth, which is the main cause of morphological defects, is a much more important process for reliable and high yielding Schottky devices as compared to PN diodes.

*Avalanche Energy*

The pulsed avalanche energy is the amount of energy that the power device can handle safely while it is undergoing avalanche breakdown. This energy is determined by the adiabatic heating of the blocking layer and the intrinsic temperature of this low-doped SiC layer. The static avalanche power density of a PN junction made using a particular material depends on its density, specific heat, and the temperature at which the intrinsic carrier density becomes close to the doping density of the voltage blocking layers (i.e. the bandgap of the material). Theoretically, the total avalanche energy is calculated to be more than 10X higher than Si devices. However, the breakdown current can become dominant over small filaments where all the breakdown microplasma is concentrated. This is true for both Si and SiC devices, and usually, material defects in voltage blocking junctions initiate these microplasmas. Experimental results on SiC PN diodes fabricated show that approximately 5X higher avalanche energy was obtained as compared to Si PN devices.

Optical observation of PN diodes undergoing $V_F$ degradation shows a concomitant formation of a certain material defect in these diodes, as shown in Figure 10. Probably the first report of this phenomenon, which were termed as ‘Bright line defects’ since they appear as mobile bright lines, was made by Konstantinov et al [9]. This was compared to the previously studied formation of ‘Dark line defects’ in Gallium Arsenide light emitting devices, where dislocation growth due to non-equilibrium carrier injection and crystal strain results in a similar forward bias degradation phenomenon. Many researchers agree that mobile and propagating crystal stacking faults are the primary cause of forward bias degradation of PN diodes [10]. This defect propagates through the entire n- base layer. It was initially proposed that the increase in $V_F$ is caused by reduced carrier lifetimes due to the formation of recombination centers from stacking faults. However, more recent results indicate that the increase in $V_F$ occurs as the stacking faults form a barrier to current flow and reduce the conduction area. A stacking fault defect is usually a two-dimensional error in the atomic stacking sequence of a polytype of SiC.

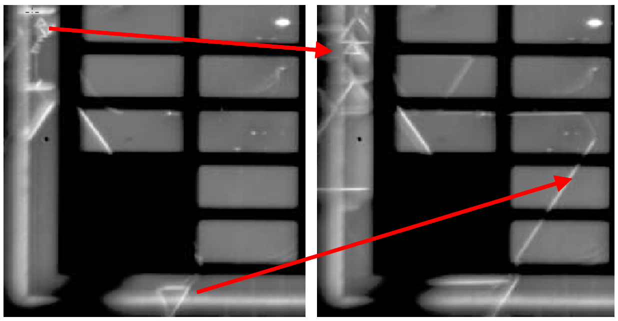

**Figure 10: Light emission measurements of a PiN diode before (left) and after (right) forward bias stress indicating growth of stacking faults.**

## 6. PRECURSORS TO SIC FAILURE

Based on previous sections, a good theoretical understanding of the unique materials defects and their effect on commonly used power devices is developed. In this section, a summary of device parameters that should be monitored to prognosticate the onset of failure mechanisms in SiC devices will be outlined.

*For Schottky Diodes:*

The on-state voltage drop and the leakage current of power Schottky diodes can give a signature of the most important parameter in Schottky contact based devices: the metal-semiconductor barrier height. Barrier height inhomogeneities cause the leakage currents to be higher than the theoretical values predicated by "pure" metal-semiconductor barrier heights. A change in leakage current over time may indicate (a) issues regarding movement of materials defects; or (b) contamination of high voltage passivation in devices. Variations in the forward I-V characteristics of a Schottky diode can also predict the severity of barrier height inhomogeneities as well as other materials defects.

*For Power MOSFETs:*

Threshold voltage and On-state voltage drop indicate the behavior of interface state densities in power MOSFETs. An increase in threshold voltage may indicate a change in the dielectric-semiconductor interface states with time. Such changes may lead to further degradation of the MIS properties of power MOSFETs. A degradation in on-state voltage drop may also show an indication of deteriorating MIS properties in power MOSFETs, which can further exacerbate the on-state performance.

*For Power BJTs and PiN Rectifiers*

As explained earlier, the degradation of on-state voltage drop in bipolar devices like PiN rectifiers and BJTs is linked to the movement of stacking faults in epitaxial layers used to form them. The variation in the on-state voltage drop is a good signature of the formation of stacking faults in these devices. Switching measurements also indicate the minority carrier lifetimes in these devices, which may be affected by many material defects as outlined previously.

To summarize, the failure signatures of various devices and their parameters are shown in Table 5.

**Table 5: Device prognostication characteristics and their materials parameter signatures.**

| Device | Device Characteristics to be monitored | MATERIAL PARAMETER SIGNATURE |
|---|---|---|
| Schottky Diodes | On-State Voltage Drop | Metal-SiC Barrier Height |
| | Leakage Current | Metal-SiC Barrier Height, Passivation |
| Power MOSFETs | Threshold Voltage | Oxide-Semiconductor Interface States |
| | On-State Voltage Drop | Channel Mobility |
| PiN Rectifiers | On-State Voltage Drop | Stacking fault propagation |
| | Switching Speed | Minority Carrier Lifetime |
| | Leakage Current | Passivation Integrity |
| Power BJTs | On-state Voltage | Stacking fault propagation |

| | | |
|---|---|---|
| | Switching Speed | Minority Carrier Lifetime |
| | Current Gain | Stacking fault, Carrier Lifetime, Base-Emitter recombination current |

## 7. CONTRIBUTORS TO POWER MODULE FAILURES

Table 6 lists the principal failure types found in power electronic modules along with the components affected the principal cause of failure, the most likely effects, their rate of occurrence and their overall severity on the health of the containing module. The table suggests that the most important aging factors to be measured in key components should be:

(1) Thermal/Mechanical Fatigue

(2) Gate Oxide breakdown in MOSFETs (TDDB)

(3) Dielectric failure

(4) Cracking Die-attach failure.

(5) Wire bonding failure.

(6) Metallization corrosion.

| Failure Type | Component Affected | Principal Cause of Failure | Effects | Severity | Rate |
|---|---|---|---|---|---|
| Dielectric Failure | - Capacitors | - Electrical Stress<br>- Over voltage<br>- Packaging failures | - Open circuit<br>- Short circuit | Catastrophic | High |
| Gate Oxide Breakdown TDDB | - MOSFETs | - Electrical Stress<br>- High temperature | - Increased $V_T$<br>- Increased $Rds_{ON}$<br>- Lower efficiency | Catastrophic | High |
| Accidental Thermal or Electrical Stresses | - ICs<br>- Diodes, SCRs<br>- BJTs<br>- FETs<br>- MOSFETs | - Over current<br>- Over voltage<br>- Large dV/dt<br>- Large temp. gradients<br>- Static discharges | - Thermal runaway<br>- Lower efficiency<br>- Device failure | Catastrophic | Medium |
| Thermal/Mechanical Fatigue | - ICs<br>- Diodes, SCRs<br>- BJTs<br>- FETs<br>- MOSFETs | - Env. Temp. Cycling<br>- Power up/down cyc. | - Contact failure | Critical | High |
| Hot Carrier Effect | - MOSFETs | - Large E field in Channel | - Short circuit | Critical | Low |
| Cracking | - ICs<br>- Diodes, SCRs<br>- BJTs<br>- FETs<br>- MOSFETs<br>- Ceramic Caps<br>- Ferrite Cores | - High g shocks<br>- Large temp. gradients<br>- Packaging failures | - Device failure | Critical | Low |
| Corrosion | -Diodes, SCRs | - Packaging Failure | - Increased R | Marginal | Low |

| | | | | | |
|---|---|---|---|---|---|
| | - BJTs, IGBTs<br>- FETs<br>- MOSFETs<br>- ICs<br>- Capacitors<br>- Resistors<br>- PCBs | - Moisture | - Contact failure | | |
| Electromigration | - ICs<br>- Diodes, SCRs<br>- BJTs<br>- FETs<br>- MOSFETs<br>- Capacitors<br>- PCBs | - Electrical Stress<br>- High Temperature<br>- High Curr. Densities | - Open circuit<br>- Short circuit | Marginal | Low |

**Table 6: Principal failure types of components in power electronic modules (power converters, motor controllers…)**

All of the models we plan to integrate have been developed and applied to silicon packaging technology. In this section we discuss some of these models and where they might fall short in modeling SiC and high temperature packaging. Packaging for wide temperature electronics is still in its infancy. Several failure modes have been observed.

For mature processes, these types of failures are generally the result of accidental occurrences during the manufacturing process. The occurrences of such events for wide-temperature devices are also possible during the normal lifetime of the components due to material fatigue or mechanical and/or thermal stresses. High-temperature packaging is the subject of research by various organizations [11]–[13]. Specific Precursors, including physical and related statistical models will have to be developed to account for this type of failure in the prognostics algorithms.

*The effects of hot spots and inadequate cooling*

The life of semiconductor devices, power semiconductors in particular, is extremely sensitive to temperature. For this reason, life acceleration by elevation of temperature is almost always used for rapid aging tests. The Swedish chemist Svante Arrhenius provided a physical justification and interpretation for the temperature dependence of a chemical reaction rate [14]. The Arrhenius formula describes the reaction rate in term of physical quantities:

$$\tau = A \cdot e^{-\left(\frac{Ea}{kT}\right)}$$

Where,

$\tau$: Life span

Ea:Activation energy (eV)

T:Absolute Temp ($^oK$)

A: Constant

k:Boltzmann's constant

Assuming that we know the life span expectancy of a component at a given temperature $T_1$, we can estimate the expected life span at a higher temperature $T_2$ using the above formula.

*Delta T vs Cycles to Failure*

WBG devices are capable of operating at higher temperatures and there are compelling reasons for a device to be designed for, and expected to operate at these extremes. At the same time, larger delta T places exponentially more stress on the material stack up used in the packaging. Even without electrical overstress, the life of the power device is accelerated simply with exposure to wider thermal excursions. Package development that fully handles the capabilities of WBG devices is still in its infancy and not widely understood. Therefore it is critical that the proposed model include functions that monitor the magnitude and direction of *changes* in temperature. From this information, the effects of incremental delta T packets are summed and an overall acceleration factor can be calculated. Coffin-Manson has proposed one such acceleration factor for temperature cycles which can be used as a baseline for this type of modeling:

$$\sum AF_{CM} = \sum (\Delta T_{stress} / \Delta T_{use})^K$$

Where,

$\Delta T_{use}$= Use Temp Cycle Swing (Avg. or Range)

$\Delta T_{stress}$= Stress or Test Temp Cycle Swing (Avg. or Range)

K=Coffin-Manson Exponent

From empirical data, we can obtain a set of curves that describe how the magnitude and quantity of thermal cycles relate to the expected mechanical life of a package. One such model, developed at SatCon, illustrates the effect that package design has on the ability to survive this type of thermal stress.

$$N_f = (\alpha_1 - \alpha_2)^{-1} 10^6 e^{(-0.0257\Delta T)}$$

Where,

$N_f$= Number of thermal cycles to mechanical failure

$\Delta T$= Temp Cycle Swing (Avg. or Range)

$\alpha_1$-$\alpha_{2s}$= Difference in CTE in ppm/$^o$C between 2 layers

The plot of this model is shown in Figure 11. These curves represent specific substrate attachment materials suitable for high temperature exposure as opposed to the relatively good stress absorption of tin and lead based soft solders. The effect of stress absorption variations needs to be integrated into this model in order to account for complex stack ups in high power converters.

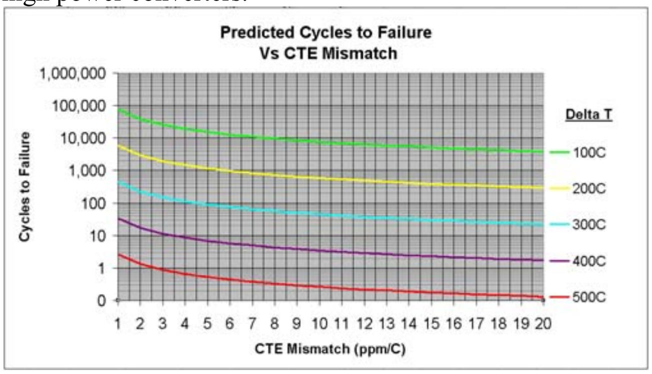


**Figure 11 Predicted thermal cycles to failure for different thermal excursions**

*Vibration Acceleration Factor*

Nearly all electronic components have traditionally been designed using time based structural and fatigue analysis methods. That is, the packaging design must withstand a load per unit of time – in the form of stress and strain. However, for many SMPS the application is in an application subject to random vibrations. In this case, a frequency-based approach for the structural and fatigue analyses is more appropriate and is the basis for random vibration testing. While the elemental stresses exerted during vibration seem small compared to the magnitude of stresses seen in a drop test or pressure test, vibration fatigue is a very real concern.

All high reliability power supplies are subjected to random vibration testing to determine whether the design meets minimum tolerance to specific power spectral densities (PSD). Some manufacturers continue vibration testing to destruction. At this point we would now know the total PSD that the package can withstand. Gauging how much a power supply has degraded during use is a matter of summing the PSD's that the device has been subjected to. Whether the PSD is small or large at any instance it is significant since it does contribute to the overall degradation of the system. As with the other acceleration factor models, we wish to implement the model as a time based function where larger magnitude spectrals use up more of the "gas gauge" than lower PSD levels.

$AF(VIB) = (W_{stress} / WT_{use})^{Mb}$

Where:

AF(VIB)=Acceleration Factor for VIBRAITON

$W_{use}$= Use PSD (Power Spectral Density) Level

$W_{stress}$= Stress PSD Level

Mb=Vibration Exponent=b/2 where b is called the fatigue parameter

*The Effects of Wide Temperature Operation - Arrhenius Acceleration Factor*

During operation, the FET is expected to be subjected to large and sometimes rapid temperature changes. These changes cause significant variations of the FET's threshold voltage and therefore its parameters [15]–[17]. Because these parameters change during the operation of the device, the FET gate driver circuitry will have to be carefully designed. For optimal results, a "smart driver" circuitry will be needed, in order to maintain the FET in optimal operating conditions. Similar driver circuits are common in high-power, high-performance motor controllers and power supplies used in industrial or military applications. In general, "*Good Architectural Choices*" in FET systems design will ensure stable and optimal operation and give the system its resilience to failure for the FET as well as other components located in the critical path of the system [18].

The measurement of Precursors can provide additional benefits in "smart driver" circuitry by adapting the gate driver characteristics to the aging power FET requirements, thus maintaining optimal operation over the useful lifetime of the component.

The predominant function used to describe failure mechanisms in the SiC device follow the Arrhenius acceleration model described previously. However, in modeling the health function this model can be expressed as an acceleration factor:

$AF(T1,T2)=e^{\{-Ea/KB(1/Tuse - 1/Tstress)\}}$

Where:

$E_a$ = is the Activation Energy (in eV - electron Volts)

$T_{use}$=Use Temperature

$T_{stress}$=Stress or test Temperature (Usually test temperature)

$K_B$= Boltzmann's Constant (0.00008617 eV/Deg K

*Temperature – Humidity Acceleration Factor, D.S. Peck Model* [19].

This type of acceleration has the highest effect on plastic encapsulated components subject to moisture ingression and corrosion effects but almost negligible on high reliability hermetic modules. Although thought to be a slow acting degradation at low temperatures, interactions with elevated temperatures can produce catastrophic failure. The Peck model integrates the arrhenius acceleration model with humidity.

AF(Temp,Hum) = AF(T1,T2) x $(\%RH_{stress} / \%RH_{use})^{Y}$

***AF(T1,T2)*** =Arrhenius Acceleration Factor from Above

***%RH**$_{use}$* = Percent Relative Humidity at use conditions

***%RH**$_{stress}$* $_s$=Percent Relative Humidity at stress or test conditions

***Y*** =Peck Humidity Exponent = 2.66

## 8. MODEL DEVELOPMENT METHODOLOGY

In the prior section, we discussed the individual models that address the components of the module prognostic control, both SiC device models and package models. In this section we discuss the algorithm concept that combines these acceleration factors in the time domain.

We would like to find a uniform mathematical model, easy to implement into an embedded system that would associate a "Health Function" for an electronic component. This function would be decreasing and normalized so as to take the value of 1 at the start of the component life and 0 at the end of the life of the given component.

Such a "Gas Gauge" function would of course be easy to interpret. We choose a formulation that describes the physical mechanisms of aging and are ultimately contributing to the final failure of each of the key components of the system. The state of each of these physical mechanisms will be measured directly or indirectly by observable quantities tabulated using the models described so far.

So each component's aging function is represented by a matrix operator operating on a vector variable representing the main parameters contributing to its aging: the time-dependent "State Vector". Usually two different component types of the module may use vectors of different dimensions.

For each of the components we would consider the main "Aging Operator" representing normal aging conditions for a given set of constant parameters. For example the "Aging Operator" of the component would be:

$$[A]_i = \begin{pmatrix} op_{11} & op_{12} & \dots & op_{1n} \\ op_{21} & op_{22} & \dots & op_{2n} \\ \dots & \dots & \dots & \dots \\ op_{m1} & op_{m2} & \dots & op_{mn} \end{pmatrix}$$

And the state vector would be:

$$\vec{V}_i = \begin{pmatrix} f_1(t) \\ f_2(t) \\ f_3(t) \\ \dots \\ f_m(t) \end{pmatrix}$$

Typically the combination of operators and vector will be chosen so as to model the main aging contributions. The various precursors would themselves form a vector that can be obtained from the above "Aging Operator" **[A]$_i$** and state vector. The general relation between "precursors" and "Aging Operator" is expected to have the form:

$$\vec{P}_i(t) = \left[ \int_0^t [A(t)]_i \bullet [S(t)]_i \, dt \right] \bullet V(t) + U(t)_i \text{ where}$$

$[A(t)]_i$ : is the normal aging operator

$[S(t)]_i$ : is the stress operator

$V(t)_i$: is the "State Vector" including all the time-dependant variables acting on the component i

$U(t)_i$: is a small probabilistic component contributing to the uncertainty on the measure of $\mathbf{P_i(t)}$

Having the general form of the expression relating the "Precursor" vector in terms of the "Aging Operator" we can anticipate the overall module health function:

$$H(t) = \prod_i \bullet \frac{1}{k} \bullet \sum_k \left( \Phi\left[t - [T]_i \bullet \vec{P}_i(t)\right]_k \right) \bullet c_i \bullet [h]_i \bullet \vec{P}_i(t)$$

where

$$\Phi(t) = \int_{-\infty}^{t} \delta(x)dx \text{ : is the Heaviside step function}$$

$[T]_i$ : is the "Terminator" operator – modeling the failure of the component **I** once $\vec{P}_i(t)$ has reached a given state.

$c_i$: is the weight of the particular component in the overall health of the module

$[h]_i \bullet \vec{P}_i(t)$: returns the normalized value of "Health" of each component.

The summation over **k** represents the degree of redundancy of a given component. For example in a Switch-Mode Power Supply (SMPS), if the power switching function on the main transformer (or coil – depending upon the architecture) is performed by two parallel FET switches in such a way that if one of the FET experiences a catastrophic failure, it causes a high-speed fuse to sever it from the system. In this case the SMPS will continue to operate at a lesser power. The same could be achieved if a FET is actually an array of appropriately interconnected FETs in the same package as it is the case for some commercial power FETs. In the above formula two parallel FET switches correspond to k=2. In this case, we notice that the result of the sum is non-zero even if one component failed. Of course, if k=1 and the given component fails, H(t) = 0**,** signaling the fact that the whole module has failed as a result of the component failure. Similar results can be obtained for capacitors and other critical components. This methodology allows us to combine the different stresses that are acting in concert to shorten the life of the power converter and so allow us to calculate, or estimate, the effective health of the system.

The power module now has a number of precursors to indicate its impending failure and we can model how each of these functions behaves over time and modify it according to the module environment. The weighting vectors allow us to track which aging operators are dominating and approaching the statistical limit of life. The model accounts for degradation over a number of environments – whether exposed to vibration, extended mild temperature, short high temperature, humidity, as well as electrical environments and overstresses.

## 9. IMPLEMENTATION PLANS -- FUTURE WORK

The work to date has focused on developing a methodology that can predict end of life through appropriate modeling, sensing, and computation. While this methodology could provide a useful tool to analyze a power converter against its design targets, the goal is to integrate the technology within the power converter's controller. Successful adoption of prognostic control will be dependent on affordable, reliable implementation that compares well against traditional approaches such as run to failure using hardware redundancy. While failure mechanisms may be characterized and modeled, and ultimately simulated, simplified models, simple sensing schemes and synthesis of a state-of-health metric based on multiple stress factors that can be calculated without excessive computation or memory requirements are all vital.

Many modern power converters, and certainly motor drives, use Digital Signal Processors (DSPs) as the primary control elements. Simpler implementations, including the motor drive of Section 4, use dedicated mixed-signal Integrated Circuits (ICs) for the high-speed switching control but use microprocessors (μPs) for system control and communication functions. Our goal is to simplify the prognostic control and prediction algorithyms to the point that they could be implemented in the embedded control available within the Power Converter without impacting the operating performance of the converter. Clearly this is dependent on the resources available with any additional sensing that is required for accurate prediction adding some amount of signal processing and I/O and then the algorithim will have both memory and computational requirements.

The focus going forward will be to:

- Continue to model failure mechanisms expanding the study to various component types, environments and failure modes.
- Calibrate and simplify the models to track aging and particularly to detect/predict more rapid end-game failures.
- Continue to develop algorithims that combine the modles.
- Derive minimal, effective set of sensors/observables for the models.
- Run experiments to collect data on aging and failure modes where poorly understood.
- Investigate device control options to extend life for application specific needs.
- Develop computationally efficient implementation of the prognostic control algorithims to facilitate cost effective application of the technology.

## 10. SUMMARY

Electric systems appear to be prone to sudden, apparently unexplained failures. By contrast, mechanical systems tend to send warning signs for a fairly long period of time before ultimate failure. The truth is that when electrical systems fail it is invariably a mechanical failure, however at such a small level that it does not send discernible warnings in terms of leaking fluids or acoustic noise. This prognostic controller technology aims to synthesize the macroscopic warning signs of dramatic aging, end of life, or imminent failure. The term "gas gauge" of health has been used in this proposal to represent the goal of an overall barometer of the state of health of the power-conditioning unit. The proposal has endeavored to describe the belief in the ability to model the aging and wearout of power converters based on detailed understanding of the mechanisms that are the weaknesses within the converter, the external forces such as temperature and vibration that drive these forces, the ability to keep the history of the power converter and finally the ability to combine all of this into a measure, or prediction, or prognostication of health. When compared to other, similar, efforts the differentiators of this work are:

- An approach to prognostication of system health based on detailed physical modeling

- A focus on reducing sensor requirements in prognostic systems through the use of physical based models and associated predictive/estimation techniques

- Efforts to characterize aging and wear-out mechanisms in the emerging SiC power device technology so that they might be applied in such a prognostic based inverter design

- Development of methodology whereby confidence levels for inverters/converters can be extended, including for WBG devices, such that they can be applied in manned and unmanned vehicle applications

- Rather than comparing a system to itself to sense or determine aging, to instead develop a signature, by correlating the sensed variables, and to compare the unit to other members of the "family", and so serve as an indicator of inherent weakness.

On the one hand we have argued that prognostic systems can be relatively simple in terms of sensing and implementation, and on the other hand we have discussed, and argued for development of, incredibly complex and detailed failure phenomena and models of failure. There is no dichotomy here, the point is to operate with the appropriate level of sensing and calculation while ensuring that any key precursor of failure is sensed if possible, or estimated if not.While we have focused on temperature effects in the work to date, which is reflected in much of the discussion in this proposal, it is important to keep all other causalities of failure in mind, and the mathematical framework we have developed supports that. An important driver of aging for electronics, in addition to temperature, is vibration. The analysis we have performed needs to be extended to investigate, characterize and model, shock and vibration driven failure mechanisms. At the same time it is critical to consider the dependence of these mechanisms, vibration and temperature. Returning to the human health comparison, just as there are initiators and promoters for human cancers so mechanical shock can clearly initiate micro-cracks that subsequent temperature cycles or vibration can cause to grow. The mathematical framework to handle this interaction without requiring excessive storage of information and so large memory requirements is the final and possibly the most significant of the contributions of this work.

## 11. CONCLUSIONS

This work endeavors to bring a structured approach to determining the aging, or ultimately the state of health, of power conversion electronics. While it is essential to measure any obvious precursors of failure, where such information is available, it is also possible to predict failure based on the life history of the power conversion unit. While there will always be some statistical spread around stress induced failure determination the confidence bands are surprisingly narrow and so motivate this predictive prognostication controller work. Preliminary efforts to develop a tensor calculation of stress have proven successful and experimental work focused primarily on temperature driven failure effects are equally promising.

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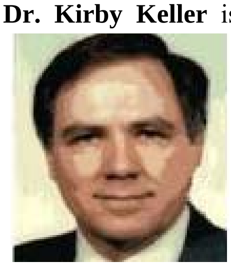
## 14 BIOGRAPHIES

**Brett Jordan** has 12 years of experience in electrical power and power electronics engineering. Upon graduating from Ohio University in 1994, with a degree in electrical engineering, he joined Stanley Electric where he worked in the Halogen bulb manufacturing area. In 2001, Mr. Jordan joined the Aerospace Power Division as project engineer, where he was responsible for the research and development of power electronic switches, motor drives, fault tolerant electrical distribution systems and components, power semiconductor devices and prognostics and health management systems. Mr. Jordan received his MSEE degree in electrical engineering from Wright State University in 1997. He holds 1 patent related to power electronics. He is a registered Professional Engineer in the State of Ohio (License #E68100).

**Dr. Jim Scofield** has been a research engineer in the Electrical Technology and Plasma Physics Branch of the Propulsion Directorate’s Power Division for over 19 years. During that time he has been involved in developmental research in the areas of photovoltaics, space power management and distribution systems, high temperature ohmic contact and packaging metallurgy, power device design and fabrication process development, plasma diagnostics, and semiconductor materials characterization including spectroscopic investigations of deep level defects and carrier transport phenomenon. Most recently Dr Scofield has been focused on the development of SiC power device and high temperature packaging technologies.



**Dr. Kirby Keller** is a Technical Fellow for the Boeing Company. He has 31 years experience in the application of intelligent systems to air and space vehicles. His current duties include

Technical Lead for the Integrated Vehicle Health Management program within the Supprot and Services Thrust of Boeing Phantom Works. In this position, he is the principal investigator and system designer for several internal research and development projects that are focused on developing a Boeing wide common architecture and best practices for IVHM. He holds a PhD in Mathematics from Iowa State University and is the author of over 40 technical papers, conference presentations, and technical reports.

**James J. Sheahan Jr.** (Jim) is a engineer/scientist in the Systems and Subsystems Technology group, part of Engineering and Information Technology in Boeing Phantom Works. Jim's technical expertise includes systems design and development, air vehicle hardware and software integration, and testing/troubleshooting of systems, subsystems and components. He was the designer/developer for the lab facilities for evaluating 8000 psi technology for advanced tactical fighters. He was responsible for writing the acceptances test and qualification test requirements, overseeing the testing and issued the qualification test reports for hydraulic components and landing gear components. He designed and developed the lab set-up and test procedures to evaluate the electromechanical actuator testing and helped develop the algorithms for actuator health monitoring. Mr. Sheahan holds B.S. degree in Mechanical/Fluids Engineering from the University of Illinois @ Chicago.

**Jeff Roach** is a Technical Fellow in the Systems and Subsystems Technology group, part of Engineering and Information Technology in Boeing Phantom Works. Jeff has over 25 years experience in actuation systems requirements definition, integration, modeling, and test. He has supported electro-mechanical actuator design, development, and integration on the Joint Unmanned Combat Air System (J-UCAS) program from 1999-2006 and has been directly involved in contracted and independent research and development of electric actuation since 1995. He has substantially participated on designs for F-15 and F/A-18 stabilator actuators, an electric drive replacement for the Space Shuttle Auxiliary Power Unit, has applied for three patents related to electric actuation control and diagnostics. Prior to 1995, Jeff held positions on the AV-8B, F-15, and F/A-18 programs designing hydraulic systems and flight control actuators as well as research and development of fluidic flight control system, 8000 psi hydraulic system technology, and hydraulic powered weapon release. Jeff holds a Bachelors degree in Mechanical Engineering from the Georgia Institute of Technology and a Master of Science in Engineering Mechanics from the University of Missouri-Rolla.

**Gregg Davis** has been a materials science engineer in the microelectronics industry for more than 20 years designing advanced packaging concepts. His range of manufacturing experience covers a large variety of technologies from traditional chip and wire assemblies to flipchip and high volume SMT products. He is an expert at high volume producibility and how materials engineering factors into reliability of devices. He has been with SatCon since May 2000 as the Engineering Manager for SatCon Technology's microelectronics division with primary focus on the automated manufacture of RF and Power microelectronics for Space and Military high reliability applications.

**Dr. Leo Casey** is VP and CTO at SatCon Technology, responsible for the design and development of power systems and electronic power products for Industrial, Utility, and Hybrid Electric Vehicle applications. Previously, he developed high frequency (1-10 MHz) DC-DC converters with associated IC controllers, inverters and controls for high-torque, direct-drive, induction and variable reluctance motors; and very high-voltage switching converter designs. Dr. Casey received the B.E. (1980) degree in electrical engineering from the University of Auckland, New Zealand. He then attended MIT as a Fulbright Scholar and ultimately received the ScD degree in 1998. He is an Editor of the Energy Conversion Transactions of the Power Engineering Society of the IEEE. He holds 6 US patents.

**Mark Prestero** has over 30 years of experience managing complex engineering programs. At SatCon he has served as Program Manager for numerous development projects, ranging from Navy undersea propulsion motor drive development, Army power converter and generator development, and several projects working on implementation of SiC devices in a variety of DoD and DoE

applications. Prior to coming to SatCon, Mr. Prestero served for 25 years as an officer in the Navy, in positions of increasing responsibility as an Engineering Duty Officer and nuclear submarine engineering officer. He ended his Naval career as Commanding Officer of the US Navy-POLARIS Missile Facility Atlantic. After the Navy Mr. Prestero worked at the Charles Stark Draper Laboratory, managing programs and robotics developments for the Defense Advanced Research Projects Agency (DARPA) and classified customers. He has a BS in Chemistry and an OE & MS, NA&ME, from the Massachusetts Institute of Technology.

**Michael Scherrer** is a consultant and team lead in software architecture and systems integration for EDS and the president of Smart-Tek Corp. Using his extensive multidisciplinary background in physics, electronics and software engineering, Michael has contributed to numerous leading-edge technologies over the last twenty two years. hold several patents in sensing techniques. Related expertise include high-power switch-mode power supplies and motor drives, real-time simulation of complex systems, AI-driven embedded systems, fault-resilient systems, condition-based maintenance, diagnostics and prognostics systems for automotive and military vehicles, measurement techniques and algorithms to determine the Remaining Useful Life of electronic component and modules. Michael studied physics at Lausanne University and Electronics at Ecole Polytechnique Federale de Lausanne in Switzerland. He has a Diploma in Physics and in Electronics.

**Dr. Ranbir Singh** is with GeneSiC Semiconductor a company he founded in 2004. He conducted research on SiC power devices first at Cree Inc. in Durham, NC from 1995 to 2003, and then at the NIST, Gaithersburg, MD. He has developed critical understanding and published on a wide range of SiC power devices including PiN, JBS and Schottky diodes, MOSFETs, IGBTs, Thyristors and field controlled thyristors. He has co-authored 90 publications in various refereed journals and conference proceedings, co-authored one book “Cryogenic operation of silicon power devices”, and is an inventor on 18 issued US patents. He has served on the Technical committee of the International Symposium on Power Semiconductor Devices and ICs (ISPSD) from 2002-04. He has twice received the IEEJ Technical Development Award for the development of ultra high voltage SiC devices.